



Conceptual Design of Low-Boom Aircraft with Flight Trim Requirement

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NASA Fundamental Aero Program

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Outline



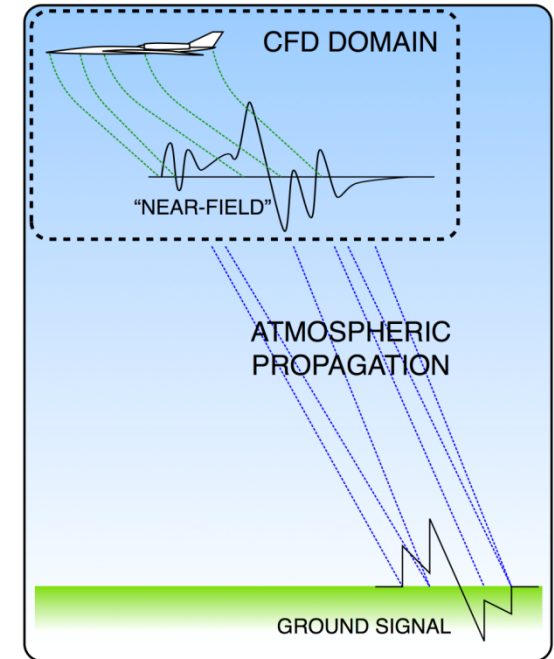
- Introduction and motivation
- Formulation of trim-feasible low-boom targets
- Verification of center of pressure sensitivity
- Application to design of a low-boom demonstrator
- Summary

Introduction and Motivation



Low-boom aircraft design

- Exploration of a complex design space with contradicting environmental and performance objectives
- Inverse design approach leverages the natural decoupling in the sonic boom analysis requirements
- Lift tailoring can lead to configurations incapable of trim through traditional fuel management techniques
- Achieving trim after configuration is shaped for low-boom can result in a compromised design



Source: Mathias Wintzer, AMA



Exploration of trim requirement

- Several lifting devices explored to help redistribute lift of low-boom configuration with minimal success
 - Canard and strake
 - Attempt to trade volume for lift fore of CG
 - Can work for some configurations but not an overarching solution
 - Can lead to structurally unacceptable configurations due to the volume trade necessary to maintain low-boom
- Approach needed to account for trim requirement early in design process
 - Leverage sonic boom analysis decoupling and inverse design
 - Introduce trim objective into the low-boom target generation process
 - Drive the design concurrently to a trimmed and low-boom state



Description of Sonic Boom Analysis

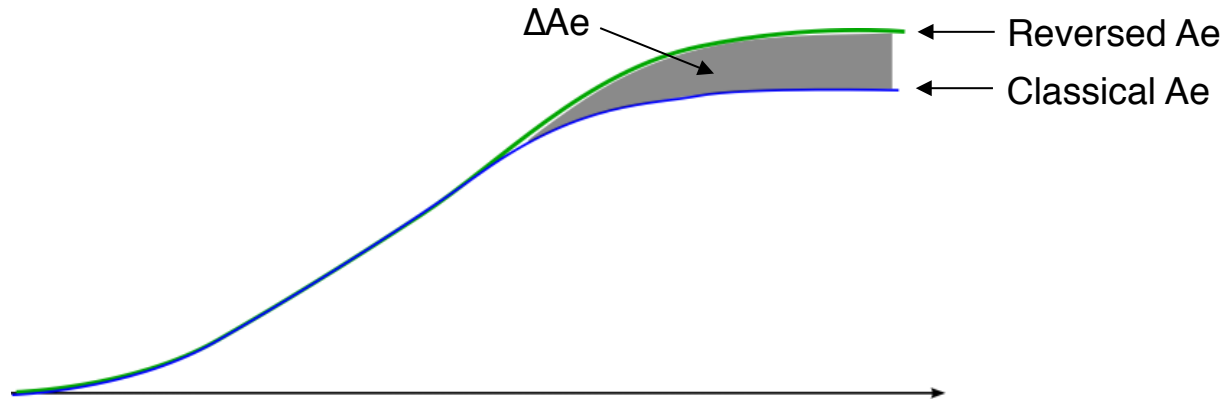
- CFD analysis with Cart3D¹
 - Inviscid CFD analysis package geared toward conceptual and preliminary aerodynamic design
 - Cartesian volume mesh rotated by Mach angle to align the shocks with the computational grid and decrease numerical dissipation
- Atmospheric Propagation with sBOOM²
 - Solve the augmented Burgers equation
 - Account for atmospheric losses due to nonlinearity, molecular relaxation, and thermo-viscous absorption
 - Propagate pressure distribution backward in time to calculate an equivalent area (A_e) in the neighborhood of the configuration

¹Aftosmis, Berger, and Adomavicius, AIAA-2000-0808., ²Rallabhandi, AIAA-2011-1278.

Formulation of Trim-Feasible Low-Boom Target



Calculation of a surrogate axial lift distribution

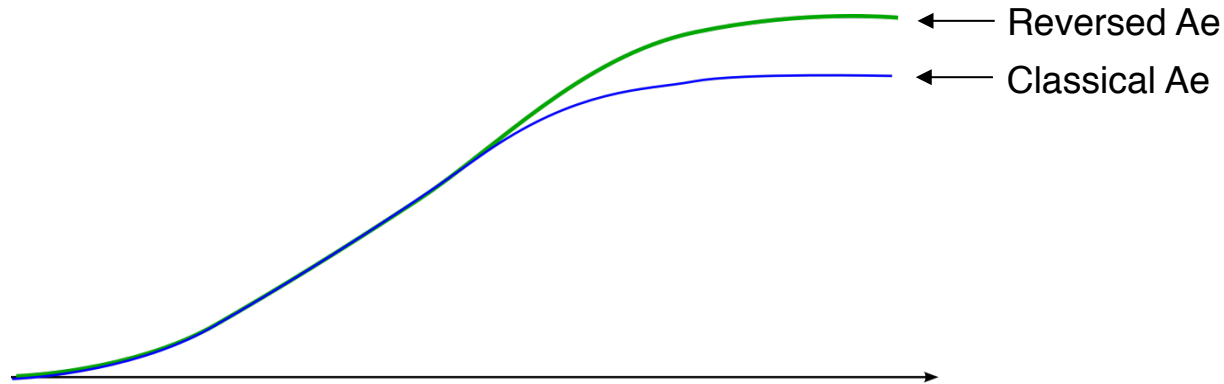


- Reversed Ae^3 is calculated by propagating a pressure distribution backward in time to a region near the configuration
- ΔAe is the error in classical Ae which fails to capture the three-dimensional flow effects associated with a real configuration
- Mixed-fidelity⁴ Ae design approach
 - Change in ΔAe due to minor shape deformation is relatively small
 - **Change in reversed Ae can be approximated by the change in classical Ae**

Formulation of Trim-Feasible Low-Boom Target



Calculation of a surrogate axial lift distribution

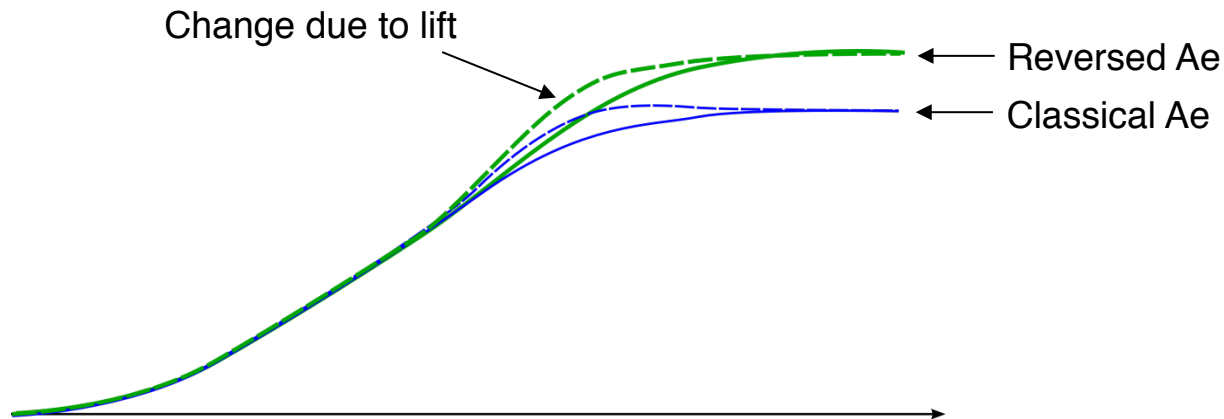


- Change in volume A_e between design iterations assumed to be small

Formulation of Trim-Feasible Low-Boom Target



Calculation of a surrogate axial lift distribution

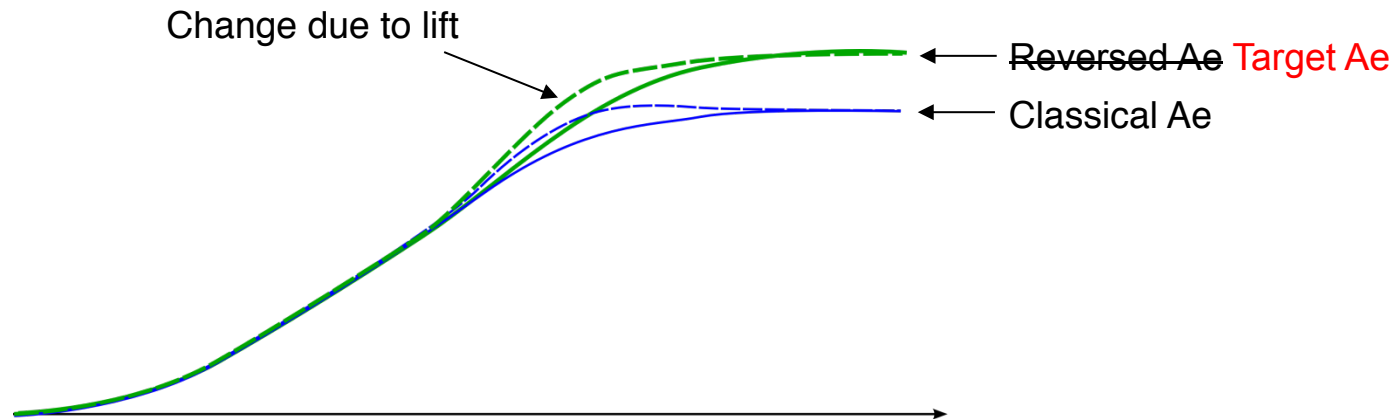


- Change in volume A_e between design iterations assumed to be small
- Change in classical A_e is a result of a change in the lift component of classical A_e
- Change in reversed A_e is a result of a **change in the lift distribution**

Formulation of Trim-Feasible Low-Boom Target



Calculation of a surrogate axial lift distribution

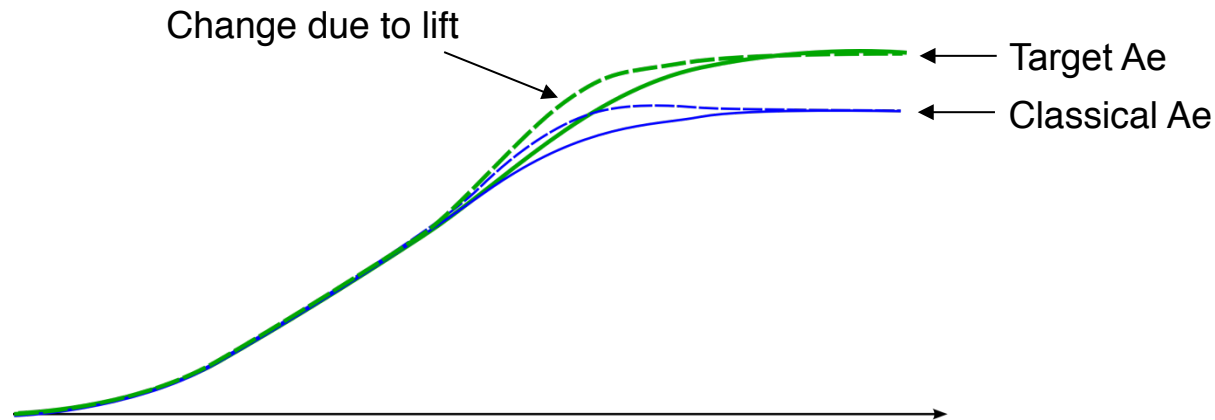


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- Leverage sonic boom analysis decoupling by optimizing a target A_e for low-boom

Formulation of Trim-Feasible Low-Boom Target



Calculation of a surrogate axial lift distribution



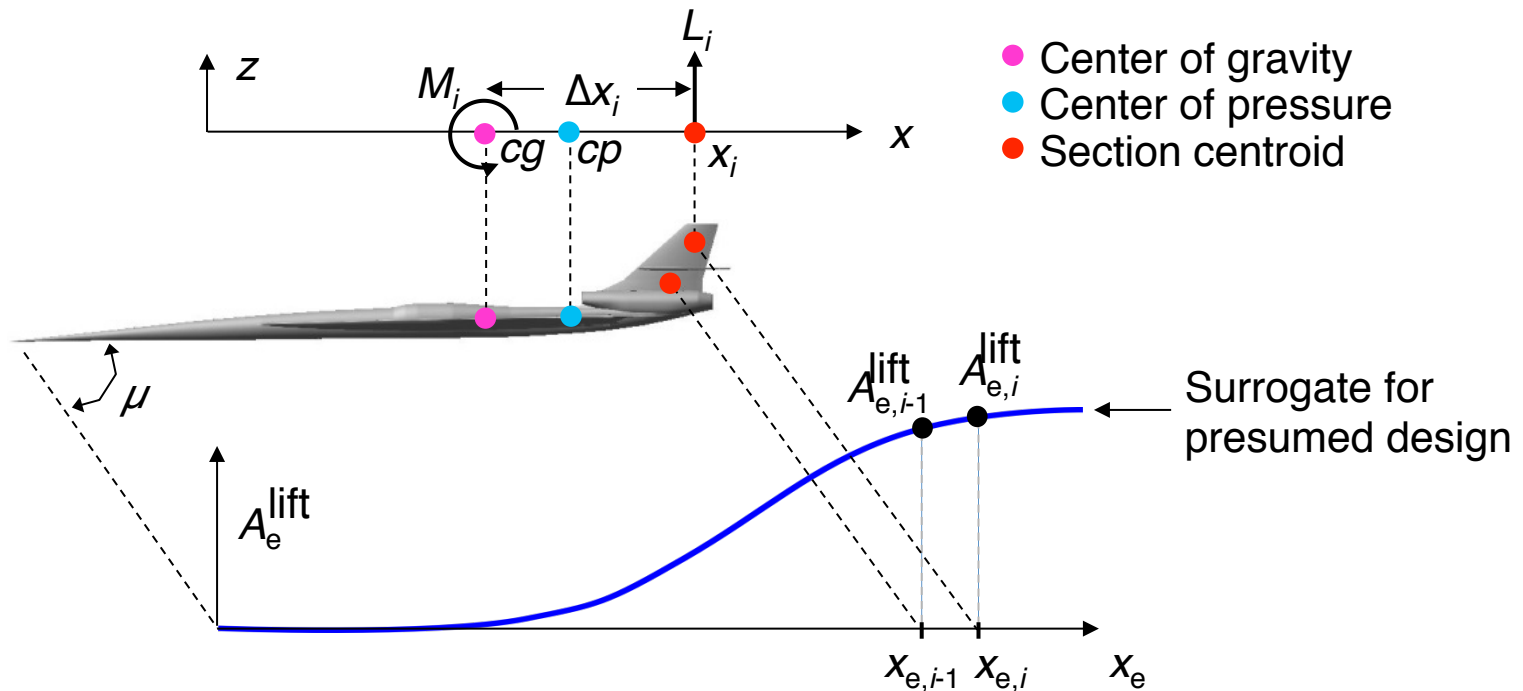
- Change in volume Ae between design iterations assumed to be small
- Change in classical Ae is a result of a change in the lift component of classical Ae
- Change in reversed Ae is a result of a change in the lift distribution
- Leverage sonic boom analysis decoupling by optimizing a target Ae for low-boom
- Surrogate lift Ae is calculated by correcting the lift Ae of the baseline with predicted change in lift Ae
- Predicted change in lift distribution is used as an optimization objective for trim

Formulation of Trim-Feasible Low-Boom Target



Calculation of surrogate center of pressure

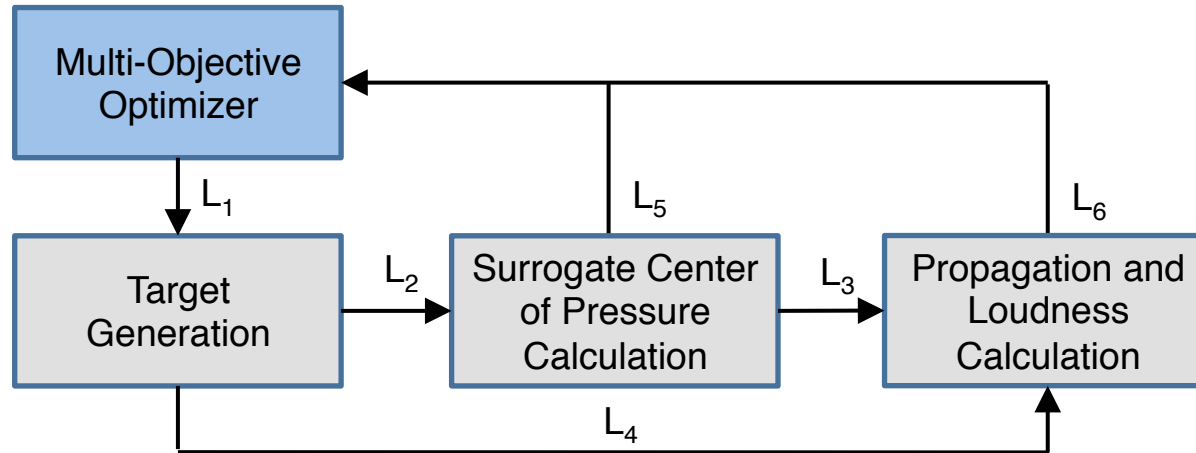
- Assume an aircraft of high fineness ratio (i.e. pitching moment due to drag is small)
- Axial lift distribution calculated from surrogate lift A_e
- Surrogate lift A_e distribution is mapped onto the baseline configuration
- Longitudinal location of section centroids calculated at each equivalent distance and used as the moment arm to calculate CP



Formulation of Trim-Feasible Low-Boom Target



Target optimization process



Inputs:

- Baseline reversed Ae
- Baseline lift component of classical Ae

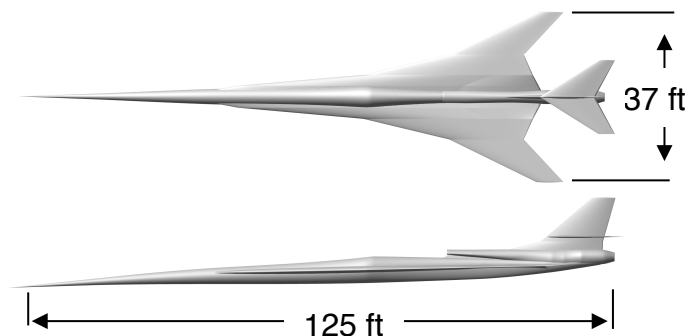
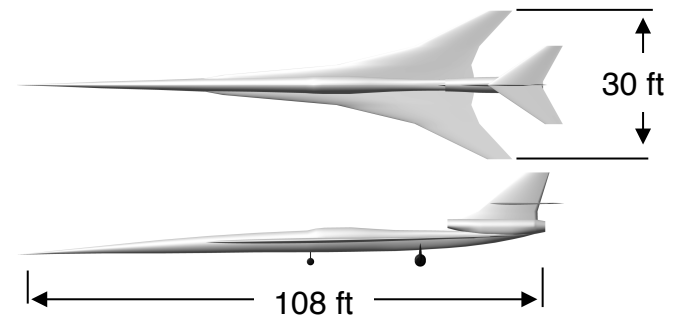
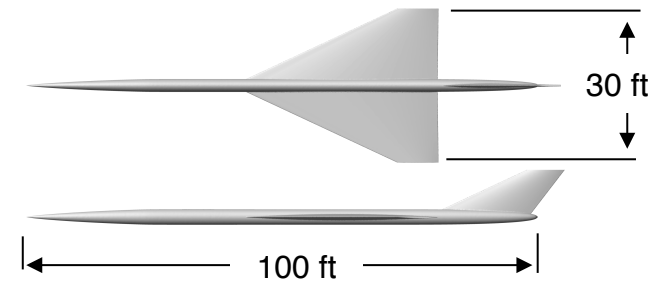
Linked Parameters:

- L_1 : Spline control points for target Ae
- L_2 : Target Ae
- L_3 : Propagation altitude based on end value of surrogate Ae due to lift
- L_4 : Target Ae
- L_5 : Change in surrogate CP
- L_6 : Perceived loudness

Verification of Center of Pressure Sensitivity



- **Case I.** Sensitivity based on shaping of a wing-body-tail configuration
 - Verify that approximated CP based only on lift closely matches CP based on pressure distribution
- **Case II.** Sensitivity based on shaping of a demonstrator concept
 - Verify sensitivity of surrogate CP on realistic low-boom concept
 - Verify that shaping of the configuration to match a low-boom target also produces the desired shift in CP
- **Case III.** Practical design of a demonstrator concept
 - Verify that a non-trimmed but low-boom feasible concept can be redesigned using a trim-feasible low-boom target

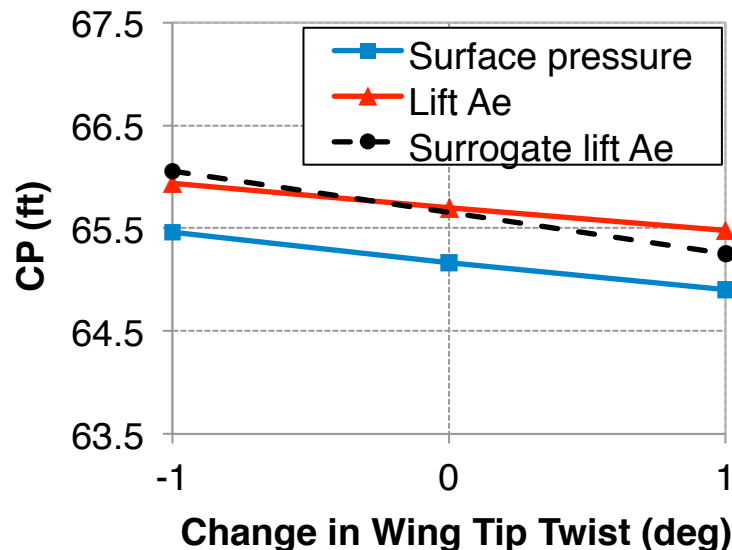


Verification of Center of Pressure Sensitivity



Case I: Sensitivity based on shaping of a wing-body-tail configuration

- Deformation consists of linear wing tip twist of -1 deg and +1 deg
- Observed good agreement between CP calculated from CFD surface pressure distribution, lift Ae, and surrogate lift Ae
- Maximum difference between the CP based on lift Ae and actual CP is 0.87 percent
- **Confirms that if contribution of drag to pitching moment is small then lift Ae is sufficiently accurate to predict CP**

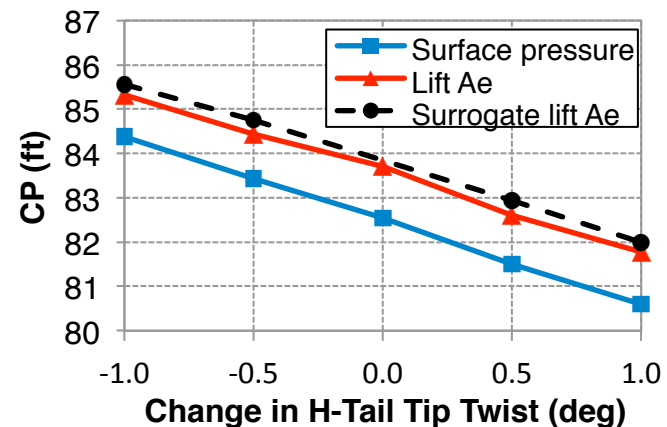
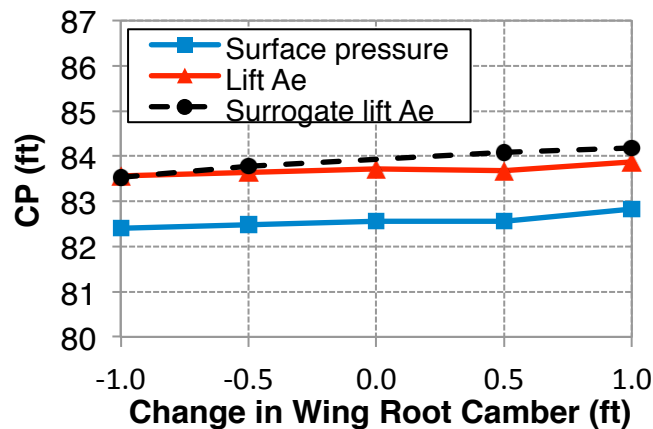


Verification of Center of Pressure Sensitivity



Case II: Sensitivity based on shaping of a demonstrator concept

- Wing camber at the root midchord is varied incrementally by 0.5 ft from -1 ft to +1 ft
- Horizontal tail tip twist is varied incrementally by 0.5 deg from -1 deg to +1 deg with a fixed incidence angle
- **Sensitivity of CP calculated with the surrogate lift Ae shows good agreement with sensitivity of CP calculated using CFD-based surface pressure distribution**

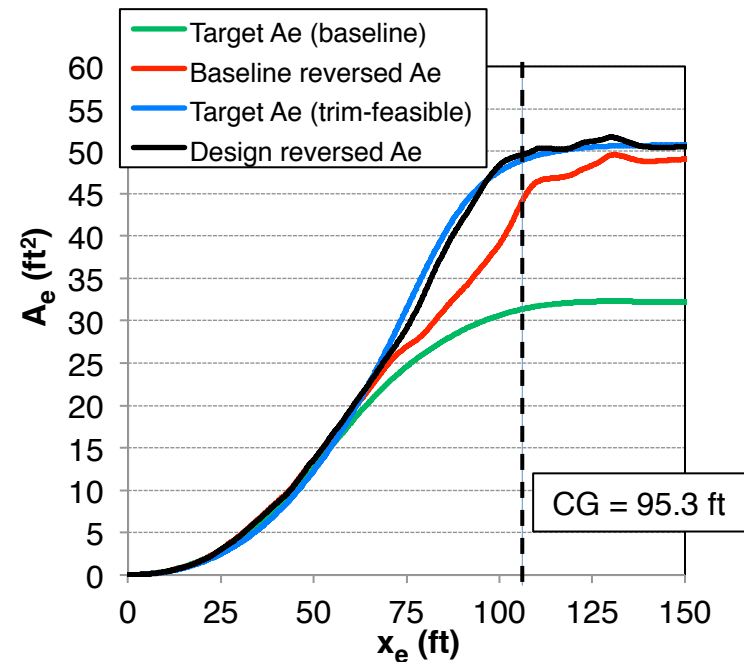
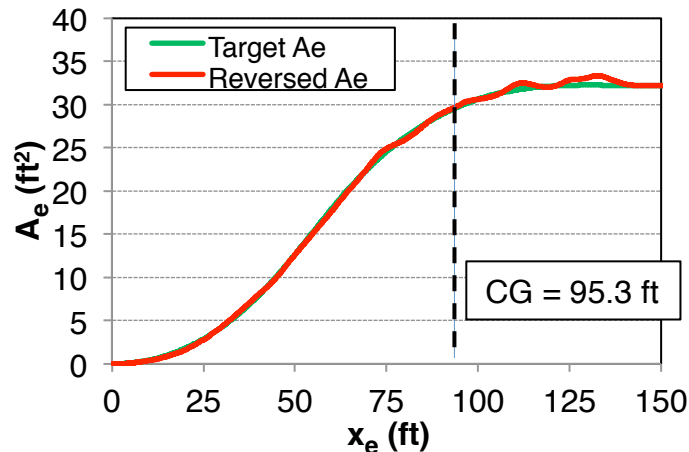


Verification of Center of Pressure Sensitivity



Case III: Practical design of a demonstrator concept

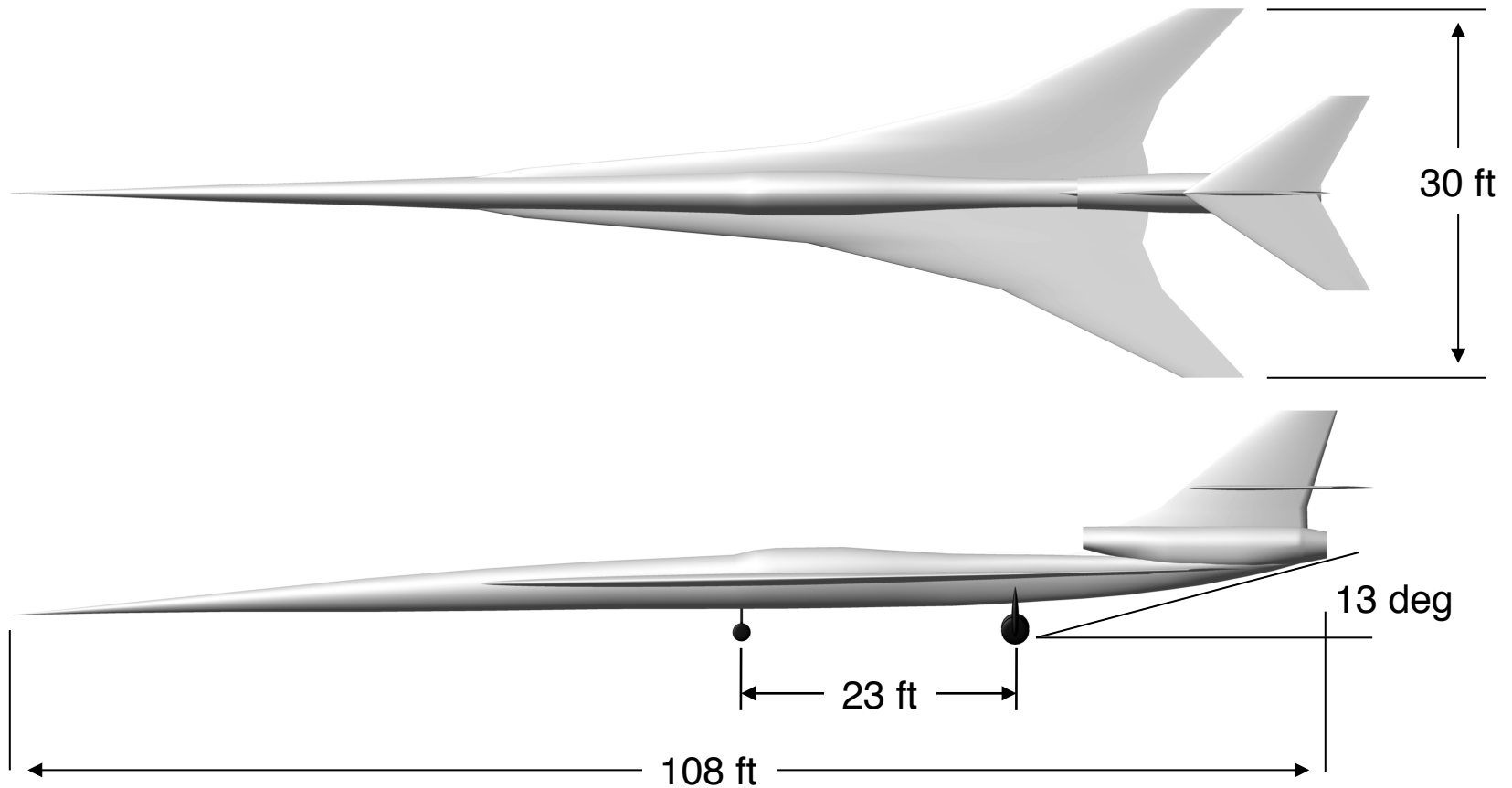
- Initially shaped to match a low-boom target A_e in the absence of trim constraint
- Untrimmed CG is 7.6 ft fore of CP
- Unable to trim by fuel management or without major layout rearrangement
- Wing redesign to match new target shifts the CP within 0.3 ft of CG**



Application to Design of a Low-Boom Demonstrator



Baseline configuration

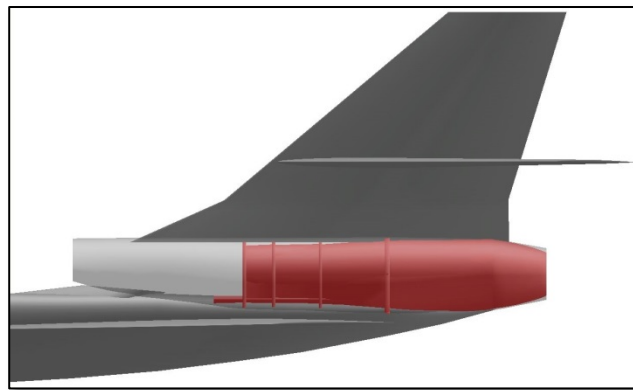


Application to Design of a Low-Boom Demonstrator



Mass properties, propulsion system, and trim analysis

- Conceptual design methods⁵ used to calculate mass properties, CG, and mission performance
- Propulsion system is a semi-embedded F404-402
- Engine performance calculated with NPSS⁶ using publically available data
- Cruise design point
 - Mach 1.6, altitude of 50,000 ft, and weight of 21,000 lb
 - Most aft CG located at 84.5 ft
 - Required forward shift in CP for trim is 1.6 ft



⁵Geiselhart, Ozoroski, Fenbert, Shields, and Li, AIAA-2011-465.,

⁶Lytle, Follen, Naiman, Evans, Veres, Owen, and Lopez, NASA TM-2000-209795

Application to Design of a Low-Boom Demonstrator



Generation of trim-feasible low-boom target

- Pareto frontier generated for PLdB and change surrogate CP using NSGA-II⁷ optimizer in ModelCenter⁸
- Altitude is allowed to vary to expand the design space
- A CP margin is used to account for uncertainty in weight calculation
- Selected trim-feasible target
 - Produces a 65.9 PLdB ground signature with a predicted forward shift in CP of 4.2 ft
 - Requires a cruise altitude of 51,700 ft

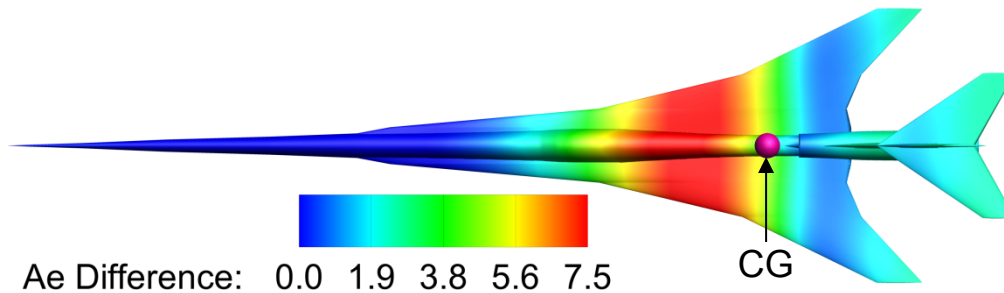
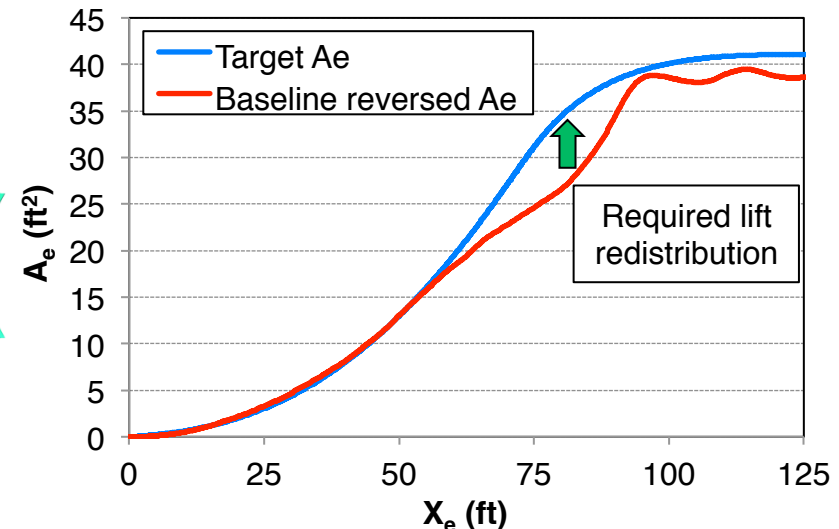
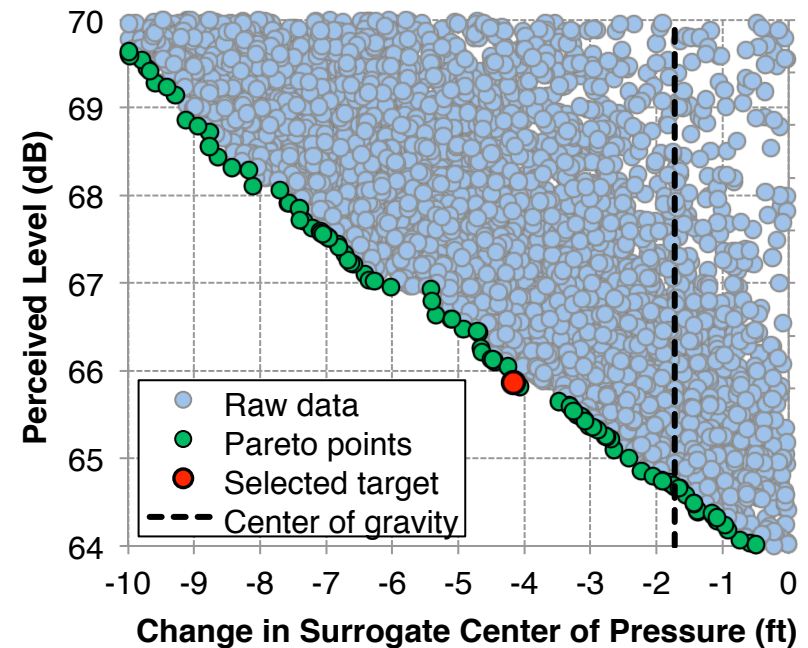


Figure shows lift redistribution requirement



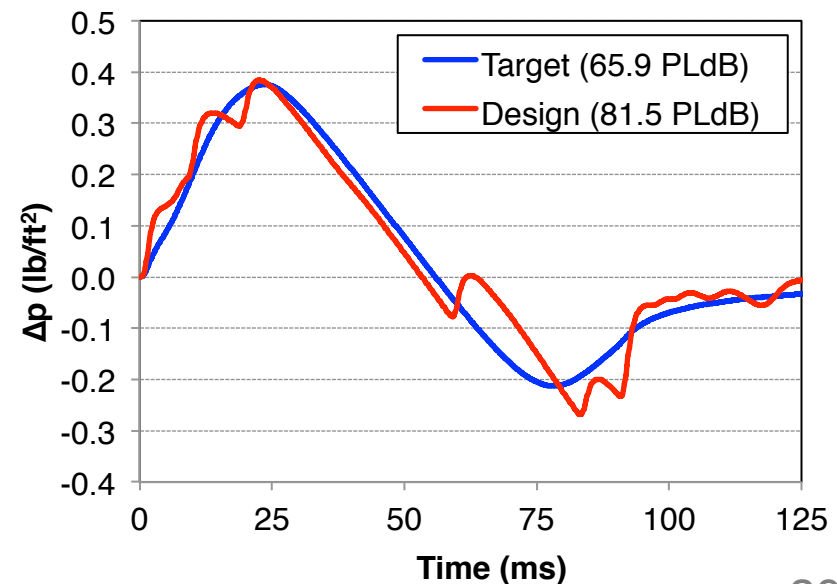
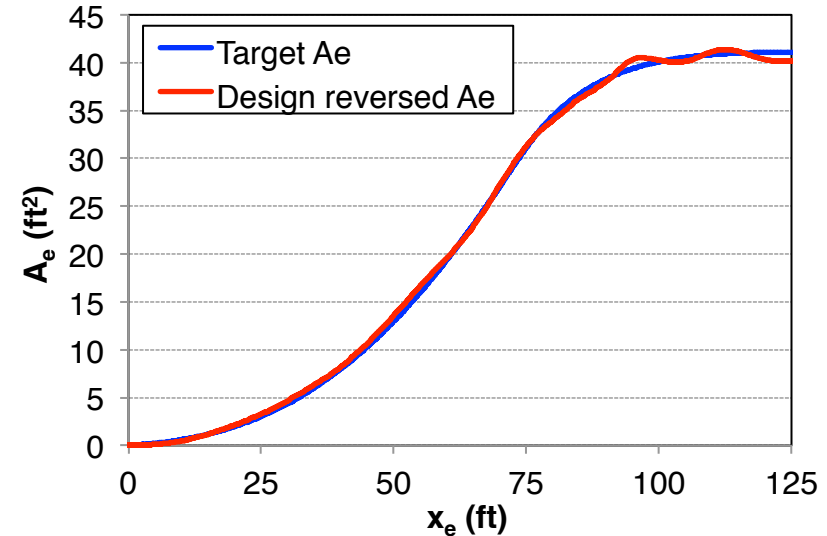
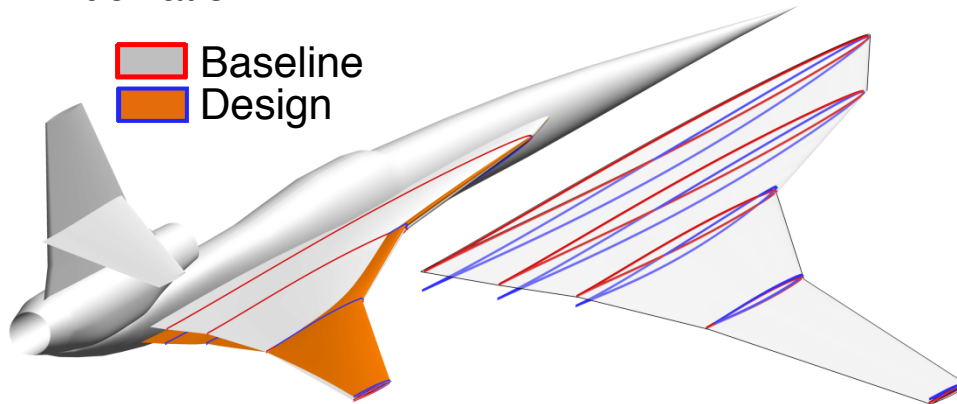
⁷Srinivas and Deb, 1995., ⁸Phoenix Integration.

Application to Design of a Low-Boom Demonstrator



Lift tailoring used to match new trim-feasible target

- Adjusted angle of attack of baseline configuration to meet CL at new cruise altitude
- Implemented wing camber parameterization scheme with 15 design variables (5 span and 3 chord locations)
- Used H-tail incidence angle to control aft lift
- Performed interactive design using mixed-fidelity approach to match the target A_e
- Used inboard wing sections to control the required lift increase fore of the CG
- Used outboard wing sections to correct aft A_e deviation



Application to Design of a Low-Boom Demonstrator



Comparison of surface pressure distribution

○ Baseline CP

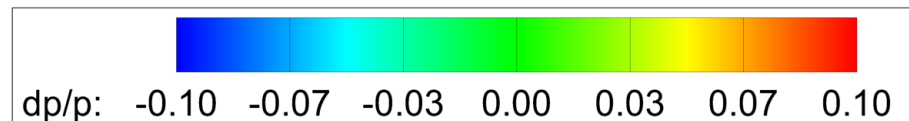
● Design CP

Baseline – Upper Surface

Design (Shaped Baseline) – Upper Surface

Design (Shaped Baseline) – Lower Surface

Baseline – Lower Surface



Summary



- Demonstrated a low-boom target generation approach that accounts for trim requirement
 - Based on mixed-fidelity design approach
 - CP calculated from an approximate axial lift distribution
 - Assume an aircraft with high fineness ratio and relatively small pitching moment contribution from drag force
- Provided three numerical cases that verify the accuracy of the sensitivity for the approximated CP
- Demonstrated the trim-feasible target generation approach for the early conceptual design of a low-boom demonstrator concept

Significance

- Provide new understanding of the design space, design feasibility, and flight conditions (i.e. altitude) required to achieve a trimmed low-boom aircraft
- Avoid costly design compromises needed to achieve trim of an aircraft initially designed strictly for low-boom



The authors would like to thank Mathias Wintzer (Analytical Mechanics Associates) and Wu Li (NASA Langley Research Center).

Questions?

References



- ¹Li, W. and Rallabhandi, S. K., “Inverse Design of Low-Boom Supersonic Concepts Using Reversed Equivalent-Area Targets,” *Journal of Aircraft*, Vol. 51, No. 1, 2014, pp. 29–36.
- ²Ordaz, I. and Li, W., “Using CFD Surface Solutions to Shape Sonic Boom Signatures Propagated from Off-Body Pressure,” AIAA-2013-2660, June 2013.
- ³Aftosmis, M. J., Berger, M. J., and Adomavicius, G., “A Parallel Multilevel Method for Adaptively Refined Cartesian Grids with Embedded Boundaries,” AIAA-2000-0808, January 2000.
- ⁴Rallabhandi, S. K., “Advanced Sonic Boom Prediction Using Augmented Burger's Equation,” AIAA-2011-1278, January 2011.
- ⁵Geiselhart, K. A., Ozoroski, L. P., Fenbert, J. W., Shields, E. W., and Li, W., “Integration of Multifidelity Multidisciplinary Computer Codes for Design and Analysis of Supersonic Aircraft,” AIAA-2011-465, January 2011.
- ⁶Lytle, J., Follen, G., Naiman, C., Evans, A., Veres, J., Owen, K., and Lopez, I., “Numerical Propulsion System Simulation (NPSS) 1999 Industry Review,” NASA TM-2000-209795, August 2000.
- ⁷Srinivas, N. and Deb, K., “Multiobjective Optimization Using Nondominated Sorting in Genetic Algorithms,” *Evolutionary Computation*, Vol. 2, No. 3, Fall 1995, pp. 221–248.
- ⁸“ModelCenter and Optimization Tools,” Phoenix Integration, <http://www.phoenix-int.com/> [cited March 2014].



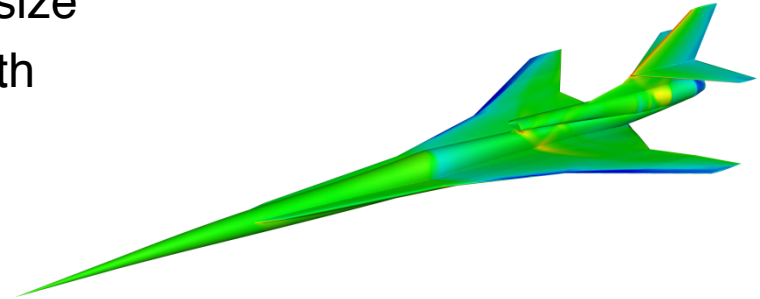
Backup Slides

Design Evolution



T-tail, S-duct F404, and 125 ft

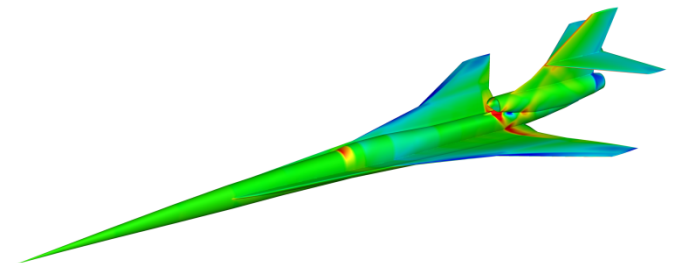
- Redesign of 140 ft configuration to reduce size
- Replaced F100 engine in 140 ft concept with F404
- Inlet shortened to reduce complexity and efficiency losses
- Successfully trimmed and shaped this configuration close to a low-boom target



T-tail, S-duct F404, 125 ft

T-tail, S-duct F404, and 108 ft

- Redesign of 125 ft configuration to further reduce size
- Successfully trimmed and shaped this configuration close to a low-boom target with 65.9 PLdB



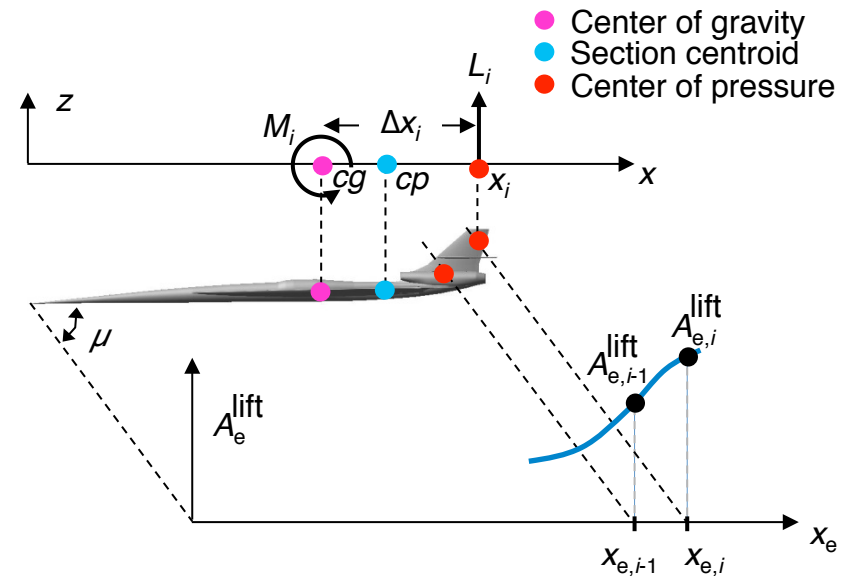
T-tail, S-duct F404, 108 ft

Generation of Trim-Feasible Low-Boom Target

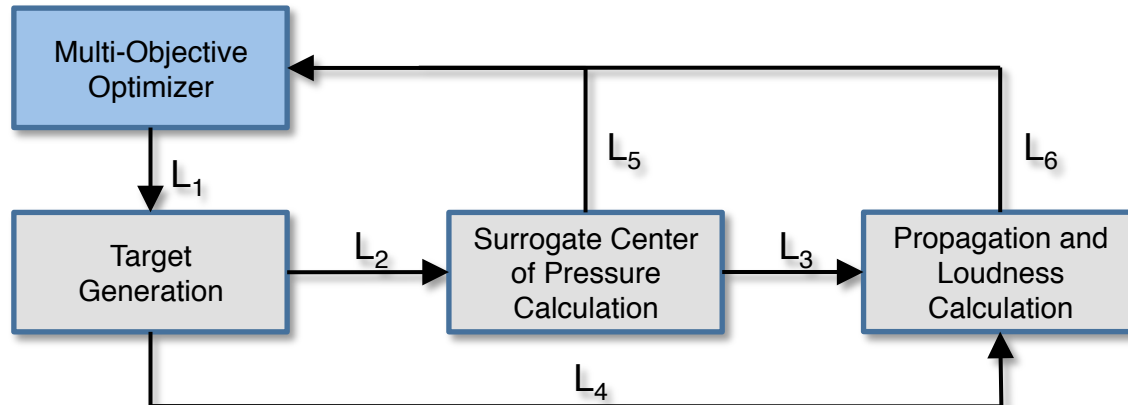


Incorporate trim requirement into the low-boom target generation process

- Based on mixed-fidelity* Ae design approach.
- Provide an approximation of CP for an aircraft configuration with a reversed Ae matching a low-boom Ae target.
- Provide new understanding of the design space, design feasibility, and cruise flight conditions (i.e., altitude) to achieve a trimmed low-boom aircraft.
- Avoid costly design compromises needed to achieve trim of an aircraft initially designed strictly for low-boom.



Target optimization process



Linked Parameters:

- L_1 : Spline control points for target A_e
- L_2 : Target A_e
- L_3 : Propagation altitude based on end value of surrogate A_e due to lift
- L_4 : Target A_e
- L_5 : Change in surrogate CP
- L_6 : Perceived loudness

Generation of Trim-Feasible Low-Boom Target



Application of trim-feasible target generation to T-tail, S-duct F404, 110 ft concept

- Initial aerodynamic and boom analysis of baseline conducted at 50,000 ft
- CP calculated with Cart3D to be $X=86.1$ ft
- Low-fidelity aft most CG ($X=84.5$ ft) calculated to determine required shift in CP for trim
- Pareto frontier generated for PLdB and surrogate CP using NSGA-II optimizer in ModelCenter
- Selected low-boom target produces a 65.9 PLdB signature with a 4.2 ft forward shift in CP
- A CP margin is used to account for uncertainty in weight calculation
- Trim-feasible target requires cruise altitude of 51,700 ft

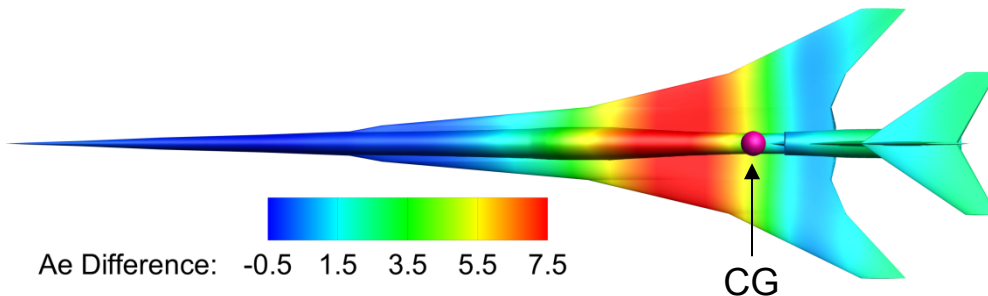
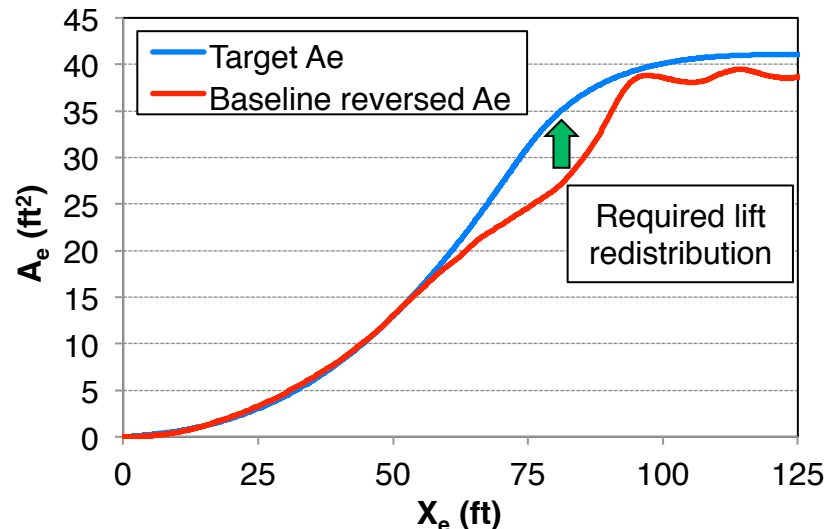
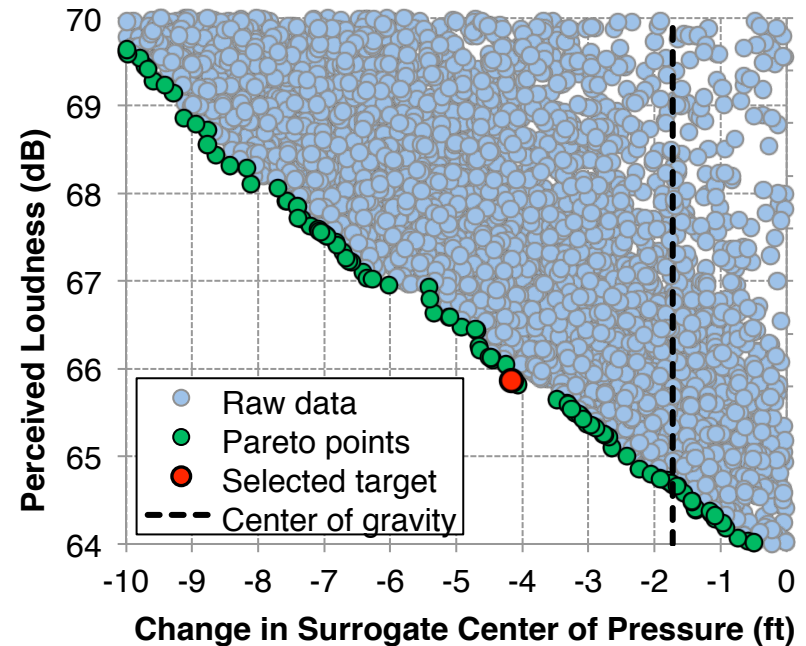
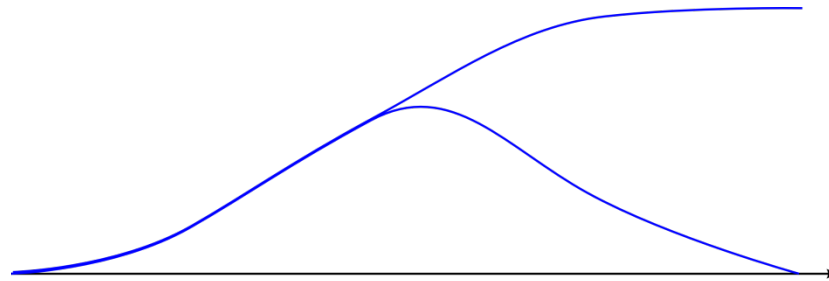


Figure shows lift redistribution requirement



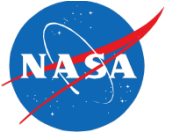
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 - Trim Problem in Low-Boom Design
- Approach, significance, and numerical results
- Formulation of trim-feasible low-boom targets
 - Calculation of surrogate axial lift distribution
 - Calculation of surrogate center of pressure
 - Optimization process
- Verification of center of pressure sensitivity
 - Sensitivity based on shaping of a wing-body-tail configuration
 - Sensitivity based on shaping of a demonstrator concept
 - Practical design of a demonstrator concept
- Conceptual design of a low-boom demonstrator
 - Description of sonic boom analysis
 - Description of baseline configuration
 - Mass properties, propulsion system, and trim analysis
 - Generation of trim-feasible target
 - Description of low-boom design and trim process
- Summary

Introduction to Trim Problem in Low-Boom Design



- Classical equivalent area distribution

Approach, Significance, and Numerical Results



Approach

- Introduce a trim objective into the low-boom target generation process by using a CP based on an approximation of A_e due to lift for a presumed design

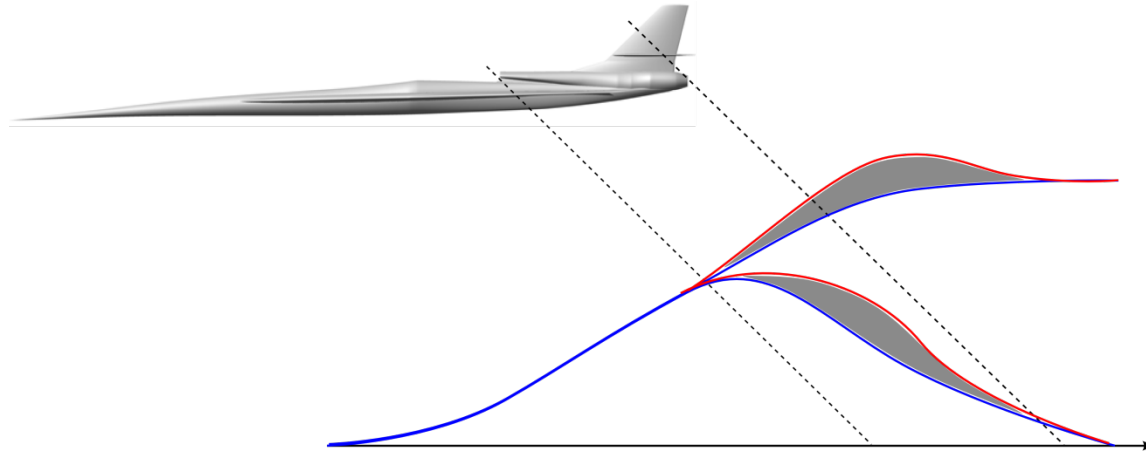
Significance

- Provide new understanding of the design space, design feasibility, and cruise flight conditions (i.e., altitude) required to achieve a trimmed low-boom aircraft
- Avoid costly design compromises needed to achieve trim of an aircraft initially designed strictly for low-boom

Numerical Results

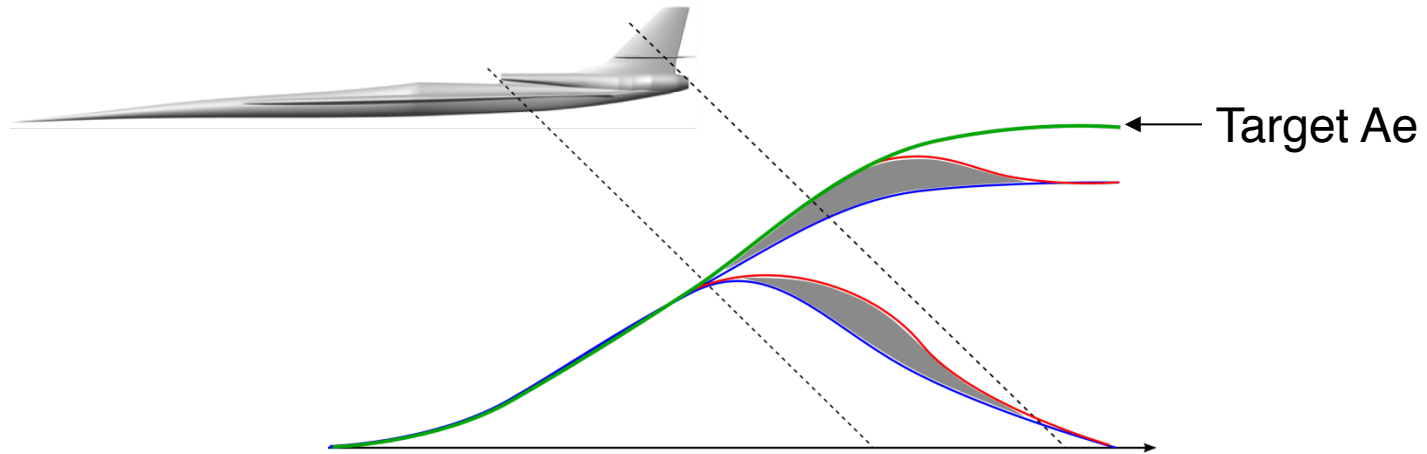
- Verification of proposed approach conducted through numerical experiments
- Application to early conceptual design of low-boom demonstrator

Introduction and Motivation



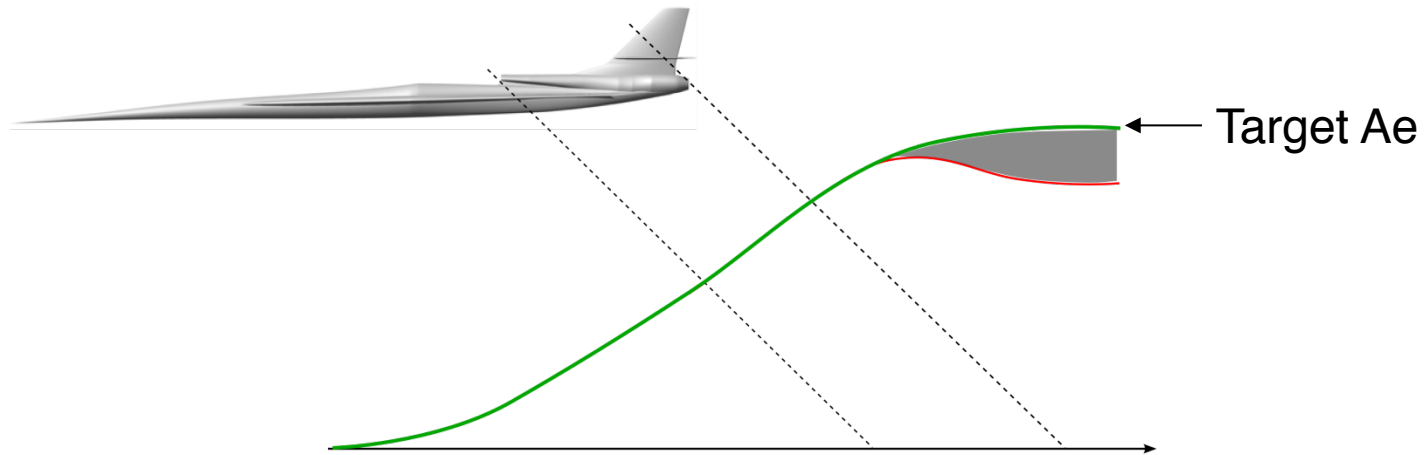
- Engine installation introduces volume requirement that results in an A_e distribution “bump” that is difficult to overcome for low-boom
- Embedded engine installation alleviates problem at the cost of integration complexity

Introduction and Motivation



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Introduction and Motivation

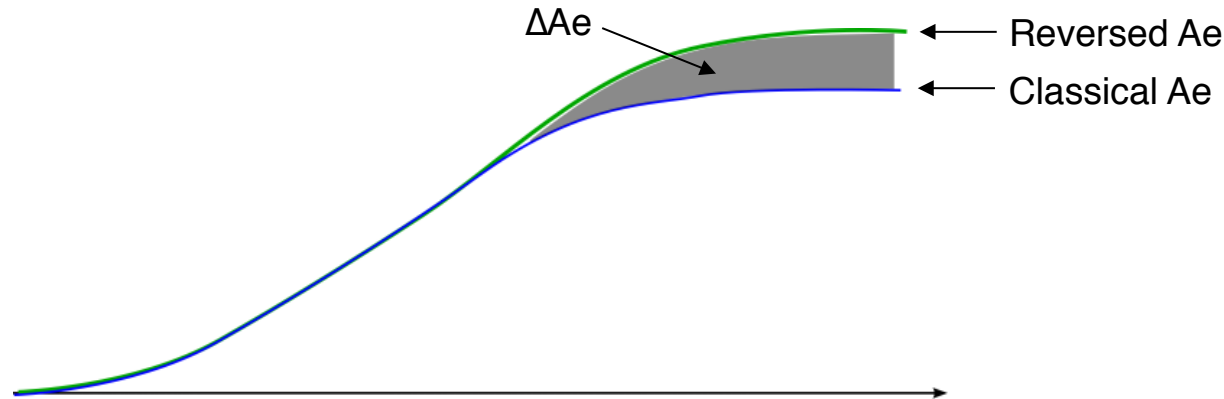


- Engine installation introduces volume requirement that results in an Ae distribution “bump” that is difficult to overcome for low-boom
- Embedded engine installation alleviates problem at the cost of integration complexity
- Deficit in Ae aft of engine is corrected through addition of volume or lift
- Redistribution of lift aft of CG is unfavorable for trim but necessary for low-boom design

Formulation of Trim-Feasible Low-Boom Target



Calculation of a surrogate axial lift distribution



- Mixed-fidelity² Ae design approach
 - Change in reversed Ae can be approximated by the change in classical Ae
- Change in volume Ae between design iterations is assumed to be small and reversed Ae of design is set equal to target Ae

$$A_e^{\text{mixed}} = A_{e,\text{baseline}}^{\text{rev}} - A_{e,\text{baseline}}^{\text{Mach}} + A_{e,\text{design}}^{\text{Mach}}$$

- Surrogate lift Ae for the design is scaled based on ΔAe of baseline configuration

$$A_{e,\text{design}}^{\text{lift}} = A_{e,\text{target}} - A_{e,\text{baseline}}^{\text{rev}} + A_{e,\text{baseline}}^{\text{lift}}$$

Conceptual Design of a Low-Boom Demonstrator



Description of baseline configuration

- Single semi-embedded engine
- T-tail empennage
- T-38 cockpit

